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Experimental investigation of the bubble separation route for an axial gas–liquid separator for TMSR

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ABSTRACT

The gas–liquid separator plays a key role in the fission gas removal system for Thorium Molten Salt Reactor (TMSR). The separation principle in swirling flows indicates that the bubbles will be gathered in the swirl chamber center. These bubbles can be collected in three ways, including through the upstream orificeonly (UO), the downstream orifice (DO) only or two orifices simultaneously (TO). As a follow-up study, this paper is focused on the effect of the bubble collection on the separator performances. To do this, experiments for each collection scheme were conducted under different Reynolds numbers and swirling numbers. The experimental results suggest that the collection ways influence the two-phase flow patterns dramatically. To compare the performances between the TO and UO, the critical backpressure and the liquid entrainment ratio were summarized. The results show that the critical backpressure for the UO is much higher than that for the TO. However, the liquid entrainment ratio for the UO is very close to that for the TO. Therefore, the selection of the separation path is of significance to the efficient operation of the gas–liquid separator.

1. Introduction

The molten salt reactor is a promising Generation IV reactor design to meet the increasing electricity demands worldwide, and therefore attracts interest to many researchers (Lin et al., 2016; Lv et al., 2016). In Ma et al. (2015) and Yin et al. (2015a,b), authors investigated the gas core formation in a gas–liquid separator applied to the fission gas removal system in the Thorium Molten Salt Reactor (Yin et al., 2015a,b). The fundamental principle for gas separation is similar to that in hydro-cyclones (Hreiz et al., 2011), i.e. bubbles dispersed in swirl flow are accumulated and coalesced into a gas core, which forms a stratified interface between phases and leads to a consequent phase separation. However, how to select a suitable separation route for the bubbles is still lack of knowledge. For the configuration of the hydrocyclone (Hreiz et al., 2011; Wang et al., 2011; Narasimha et al., 2012), there are an underflow orifice and overflow orifice, which receive the liquid phase and the gas phase, respectively. However, for the gas–liquid separator introduced in Yin et al. (2015a,b), both the downstream orifice and the upstream orifice are designated for receiving the gas phase. Hence, there are three possible routes to separate the bubbles, namely, through the downstream orifice (DO), through the upstream orifice (UO), and through two orifices (TO). To have a deep understanding of the effects of the bubble separation routes on the separation performances, an experimental study focusing on three separation routes was carried out. The structure of this paper is arranged as follows: the experimental specifications are detailed in Sections 1 and 2 presents the experimental results and discussions. Finally, the effects of separation routes on the back pressure and the liquid entrainment ratio are summarized in Section 3. The conclusion is drawn in Section 4.

2. Experimental procedure

The experiment was conducted in the experimental apparatus used in our previous study (Yin et al., 2015a,b). Fig. 1 illustrates the modified experimental system, in which the separator configuration is composed of a swirl vane, a swirl chamber, and a recovery vane. The three separation routes were obtained by controlling two valves installed in the branch pipes which connect the downstream orifice and the upstream orifice with a water tank. The mode in which both valves are open and the light phase will flow through the downstream orifice and the upstream orifice simultaneously is denoted by TO mode. The mode in which the valve V2 is closed and the valve V1 is open and the gas phase flows only through the downstream orifice receives is denoted by DO mode.

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Nomenclature

P_{outc}	critical back pressure
Q_{Lin}	liquid phase volumetric flow rate at the separator inlet
Q_{Lout}	liquid phase volumetric flow rate at the separator outlet
Re	Reynolds number
S	Swirl number
λ	liquid entrainment ratio

And the mode with V1 closed and V2 open, under which the gas phase flows through the upstream orifice is named by UO mode. The flow conditions covers four Reynolds numbers, which is defined based on the swirl chamber diameter and the upstream averaged velocity, ranging from 56,419 to 141,048. Two swirl vanes with different outlet angles were adopted to elucidate the effects of the swirl number, which is defined as the ratio of the axial flux of azimuthal momentum to the axial flux of axial momentum times the equivalent radius. Based on the method proposed by Beer (Chigier and Beér, 1983), Eq. (1) was adopted to calculate the geometrical swirl number, where R_o denotes the inner diameter of the swirl chamber, R_i is the diameter of the hub of the swirl vane, and α is the outlet angle. With Eq. (1), the swirl numbers for two swirl vanes are 0.77 and 1.71, respectively.

$$S = \frac{1}{2}\frac{1-(R_i/R_o)^4}{1-(R_i/R_o)^2}\tan\alpha \qquad (1)$$

As is introduced in Alekseenko et al. (1999), to achieve a successful bubble separation, two objectives should be fulfilled. The first objective is the formation of a gas core with clear interface and straight-line shape for bubbles evacuating from the separator (Sripriya et al., 2013; Li et al., 2015). The second objective for economical operation is the liquid entrainment ratio λ, defined as Eq. (2) (Q_{Lin} is the volumetric flow rate at the separator inlet, and Q_{Lout} is the volumetric flow rate at the separator outlet), should be as small as possible. The following discussion will focus on the effects of separation routes on the air core formation and the liquid entrainment ratio.

$$\lambda = \frac{Q_{Lin} - Q_{Lout}}{Q_{Lin}} \qquad (2)$$

3. Results and discussion

3.1. Two phase pattern development with Reynolds number

The flow pattern evolutions under the conditions listed in Table 1 were visualized by high speed camera. As was introduced in our previous study (Yin et al., 2015a,b), the gas core formation depends on the variations in the back pressure. Figs. 2–4 show the flow pattern evolution for $S = 0.77$ (TO) under different Reynolds numbers, which indicates the gas core formation in the TO mode is featured by a four-stage evolution process including “air core with suction”, “tadpole shaped core”, “cloudy core” and “rod core”. The “rod core” is presented as the final state of the evolution and also the expected flow pattern under which the bubbles are separated completely. The back pressure at the separator outlet which promotes the occurrence of “rod core” is defined as the

Table 1
The test conditions indicating 3 × 2 × 4 = 24 operating points.

Variable	Value
Mode	UO, DO, TO
S	0.77, 1.71
Re	56,419, 98,734, 119,890, 141,048

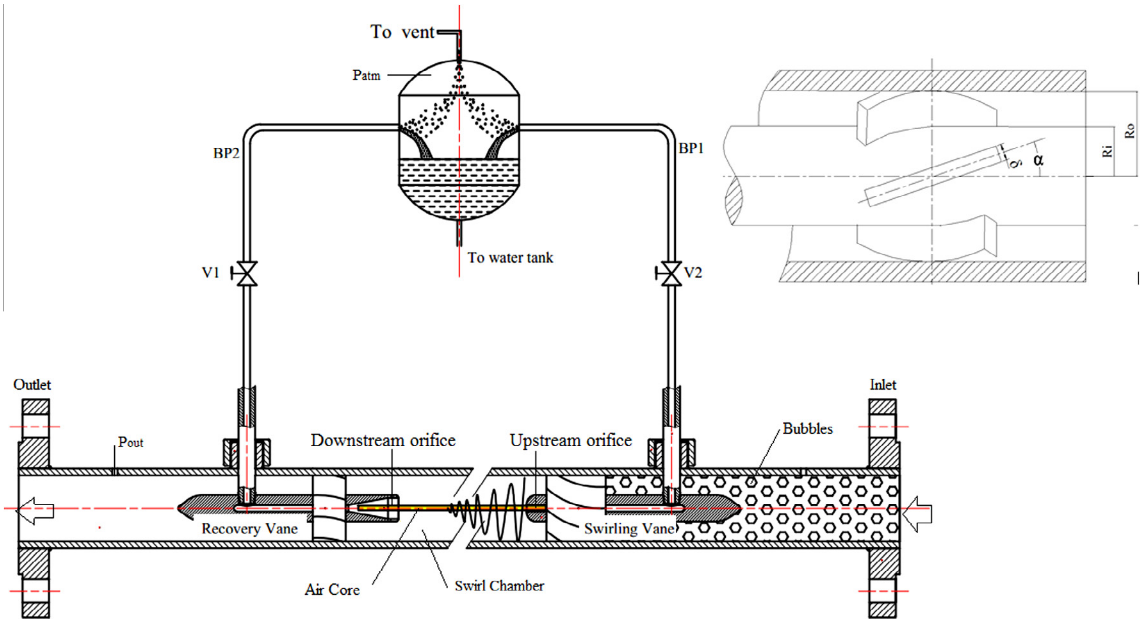

Fig. 1. The experimental rig (V1 and V2 denote the control valves used to change the separation route).